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Weakening of Indian Summer Monsoon in Recent Decades

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ABSTRACT

The analysis of 43 years of NCEP-NCAR reanalysis data and station observations reveals the connections between tropospheric temperature variations and the weakening of the Indian summer monsoon circulation. The Indian summer monsoon variation is strongly linked to tropospheric temperature over East Asia, showing significant positive correlations of mean tropospheric temperature with all-Indian summer rainfall and the monsoon circulation intensity. The result shows that Indian summer monsoon circulation underwent two weakening processes in recent decades. The first occurred in circa the mid-1960s, and the other occurred in circa the late 1970s. The finding indicates that the mean tropospheric temperature may play a crucial role in the weakening of the Indian summer monsoon intensity via changing land-sea thermal contrast. The role of the tropospheric temperature contrast between East Asia and the tropical area from the eastern Indian Ocean to the tropical western Pacific is to weaken the Indian summer monsoon circulation.

Key words: Indian summer monsoon, tropospheric temperature, East Asia, land-sea thermal contrast

1. Introduction

Numerous studies have examined questions relevant to the Indian summer monsoon, based on different Indian summer monsoon indices (Webster and Yang, 1992; Kawamura, 1998; Goswami et al., 1999; Wang et al., 2001; etc.). Generally, the generation of the Indian summer monsoon is attributed to the land-sea thermal contrast. Using simple linear models with prescribed heating, Webster (1972) and Gill (1980) established a relationship between the strength of the heating over the South Asian region and the magnitude of the regional vertical shear. The Indian summer monsoon may be thought of as the low-frequency baroclinic-Rossby wave response to the heating. Based on this simple theory, Webster and Yang (1992) defined the Indian monsoon index as the vertical shear of the zonal wind averaged over the area 0°–20°N, 40°–110°E. In fact, as Chen (2003) suggested, three basic ingredients are included in the commonly accepted maintenance mechanism of a summer monsoon circulation: (1) the land-ocean differential heating, (2) a monsoon high (oceanic trough) at upper levels and a thermal low (anticyclone) over the continent (ocean) at lower levels, and (3) the coincidence of a monsoon high (thermal low) with a divergent (convergent) center. Consequently, summer monsoon circulation variations should show a close relationship with the atmospheric circulation variations in the troposphere.

Recently, the long-recognized negative correlation between Indian monsoon rainfall and ENSO has weakened rapidly during recent decades. Many previous studies have explored the possible reasons for the weakening of the ENSO-Monsoon relationship (Webster and Palmer, 1997; Kumar et al., 1999; Chang et al., 2001; Kripalani et al., 2001; etc.). Kripalani et al. (2001) attributed the weakening of the ENSO-Monsoon relationship to the following reasons: (1) modulation by the decadal variability of monsoon rainfall; (2) chaotic nature of monsoons; (3) linkages with the Inidan Ocean Dipole Mode; (4) global warming; and (5) Atlantic circulation variation.

Actually, besides the rapid weakening of the ENSO-Monsoon relationship, the Indian summer monsoon itself also showed a weakened epoch after circa the mid-1960s (Kripalani and Kulkarni, 2001; Kumar and Dash, 2001). However, the weakening trend after circa the mid-1960s was rarely examined before. In contrast, much attention has been paid to the interdecadal climate shift that appeared in the 1970s. For example, Wang (2001) revealed a weakening trend in the Asian summer monsoon since the end of 1970s. Many previous studies attributed the regime shift that

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occurred in the late 1970s to variations relevant to the tropical ocean and the Walker circulation.

It is well known that the onset of the Asian summer monsoon is concurrent with the reversal of the meridional temperature gradient in the upper troposphere south of the Tibetan Plateau (Li and Yanai, 1996). On interannual timescales, the Indian monsoon rainfall has a strong and positive correlation with the pre-monsoon spring tropospheric temperature anomaly (Verma, 1980; Parthasarathy et al., 1990; Singh and Chattopadhyay, 1998). Therefore, most previous studies on tropospheric temperature and the Indian monsoon rainfall have focused on the possible influence of tropospheric temperature variations (TTV) on the Indian monsoon rainfall, but they have rarely examined the connections of the TTV with the weakening of the Indian summer monsoon, particularly with the Indian summer monsoon circulation intensity. Although there are many factors influencing the Indian summer monsoon, such as the sea surface temperature in the Indian Ocean (Zveryaev, 2002), the Indian Ocean Dipole Mode (Saji et al., 1999), Eurasian snow cover (Kripalani and Kulkarni, 1999; Fasullo, 2004), the Atlantic circulation variation (Chang et al., 2001), global warming and human activities, and so on, the real effects of all these factors on the Indian monsoon must depend on the atmospheric circulation because the Indian summer monsoon is itself associated with the diabatic heating of the atmosphere during boreal summer. The objective of the present study is to examine the connections. Through the present study we demonstrate the role of the TTV in the weakening of the Indian summer monsoon circulation in recent decades, which has been ignored before.

2. Data

The data used in this paper, including sea level pressure (SLP), geopotential heights, air temperatures, and zonal winds at each standard level from 1000 hPa to 200 hPa covering a 43-yr (1958–2000) period, were taken from the National Centers for Environment Prediction-National Center for Atmospheric Research (NCEP-NCAR) re-analysis dataset (Kalnay et al., 1996). In addition, all-Indian monsoon (June-September) rainfall (IMR) data was digitized from Liu and Yanai (2001). Summer (June–September) rainfall (1951–1994) of 28 stations in North China and monthly mean SLP at Beijing (39.48°N, 116.28°E) (1951–2000) were obtained from the National Meteorological Center of China. In addition, as an important complement to the NCEP/NCAR reanalysis dataset, this study also used the surface air temperature observations at Beijing (39.48°N, 116.28°E) (1940–2002) derived from the more than 7200 independent stations in the world (Hansen et al., 1999), obtained from the Goddard Institute for Space Studies, NASA (http://www. giss. nasa. gov /data /update /gistemp/); for further information about the dataset, see Hansen et al. (2001). We also utilized the global topographical height data on a $2.5° \times 2.5°$ grid to exclude the impact of the Tibetan Plateau in calculating mean tropospheric temperature. All of the data were averaged for the four summer months June, July, August and September.

3. Analysis

3.1 *Indian summer monsoon and their relationship with TTV on interannual timescales*

In the present study, supposing that the mean and variance of all the data do not change with time, we calculate correlation coefficients (CCs) of the IMR and Webster and Yang's monsoon index (hereafter the WY index) with tropospheric air temperature to reflect their connections on interannual timescales.

Correlations of the IMR and WY index with temperature at each standard pressure level from 1000 to 200 hPa show that the most significant correlations mainly appear in the mid-high troposphere rather than near the surface (figures not shown). This is very consistent with the conclusions reached by Liu and Yanai (2001). After excluding the Tibetan Plateau's terrain influence, we first calculated mean temperature from 850 hPa to 200 hPa, and then calculated CCs of the mean tropospheric temperature with the IMR and the WY index, respectively. The results (Fig. 1a) indicate significant positive correlations emerging over the west of 90°E and the north of 20°N and East Asia, with maximum positive CCs over northwestern parts of India extending westward to Iran. Figure 1b shows that significant positive correlations lie over the north of 25°N from North Africa extending to East Asia, with concurrent negative correlations in the south of 10°N. The spatial distribution of CCs reflects influences of the tropospheric thermal contrast on the Indian summer monsoon circulation. This demonstrates clearly that the Indian summer monsoon activities exhibit a strong linkage to tropospheric temperature variation over East Asia. Wang et al. (2001) also pointed out that a strong (weak) Indian summer monsoon corresponds well to the equivalent barotropic anticyclonic (cyclonic) anomaly over East Asia. Therefore, the TTV over East Asia might play a role in affecting the Indian summer monsoon circulation.

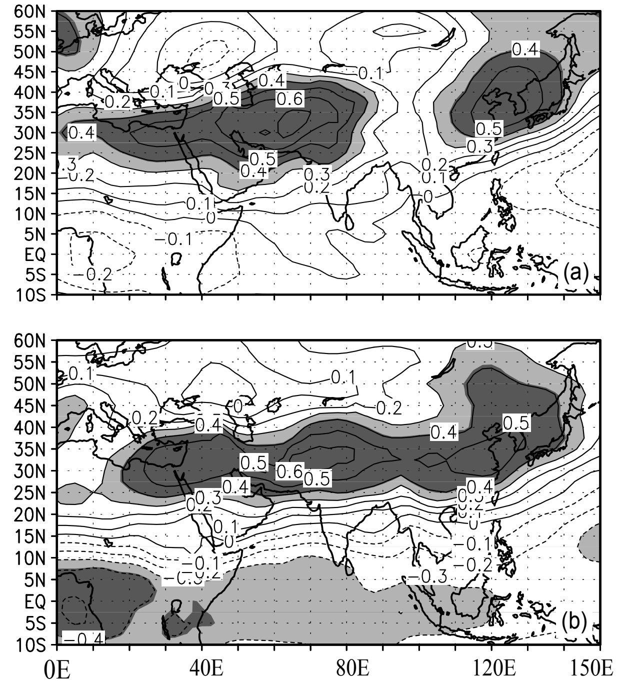

Fig. 1. Spatial distributions of CCs of the tropospheric mean temperature averaged from 200 hPa to 850 hPa with (a) the IMR, (b) the WY index. Interval is 0.1. The light and heavy shaded areas denote CCs above the 0.05 and 0.01 significance levels, respectively.

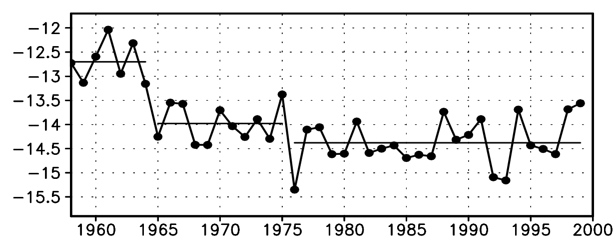

Fig. 2. The time series of the regionally averaged (35°–50°N, 100°–130°E) summer mean tropospheric temperature (Units: °C).

3.2 *Weakening of Indian summer monsoon circulation in recent decades*

The above analysis indicates that variations in both Indian summer monsoon circulation intensity and the IMR are closely related to the TTV over East Asia. Interannual variations of regional-averaged (35°–50°N, 100°–130°E,) summer mean tropospheric temperature (SMTT) are shown in Fig. 2. Obviously, there are two declining variation processes shown in the time series of the SMTT, and the major turning points are found to be at 1964 and 1975, respectively. Many investigations have suggested that a climate state shift (or regime shift) that occurred in the late 1970s is closely related to interdecadal variability of the tropical ocean (cf. Hare and Mantua, 2000), whereas, the regime shift that occurred in circa the mid-1960s deserves attention because only a few studies noticed this phenomenon, except for some studies on summer rainfall in North China (Yan et al., 1990, 1991; Ikeda et al., 2001).

During the period 1958–1964, the SMTT over East Asia was obviously higher than the long-term climatic average (Fig. 2), and corresponded with a strong thermal depression over the Asian continent (see section 4). In the following period of 1965–1975, the SMTT decreased remarkably over East Asia. Since 1976, the SMTT decreased once again. Chen et al. (1992) suggested that the thermal contrast between the continent and the adjacent Pacific Ocean is the primary factor for the decadal-scale variation of monsoon activity of China.

From the interdecadal variation point of view, the Indian summer monsoon circulation experienced a continuously weakening process during the last three dedades (Fig. 3). After the mid-1960s, the Indian summer monsoon circulation shows an apparent decaying trend, which is very consistent with the results by Kripalani and Kulkarni (2001). One can see that the decaying trend is nearly independent of the running mean methods. In order to depict possible connections between the SMTT and the Indian summer monsoon on interdecadal timescales, this paper executed a Butterworth band-pass filter to all the data (Murakami, 1979). A maximum spectrum analysis of the IMR shows that the Indian summer monsoon fluctuations involved the predominant 18-yr period (figures not shown). Therefore, the central frequency of the band-pass filter corresponds to a period of circa 18 years, and the periods of the two half frequencies correspond to 8 years and 40 years, respectively. Figure 4 shows the spatial distributions of CCs of the filtered IMR and WY index with the SMTT. There are significant positive correlations over East and Northeast Asia, with maximum CCs covering the whole Korean Peninsula (Fig. 4a). Figure 4b shows, however, that although maximum CCs also occupied East Asia, their location is remarkably shifted to the south compared to Fig. 4a. This verifies that both the IMR and the Indian monsoon vertical shear exhibit a close association with the SMTT over East Asia on interdecadal timescales. We also noticed that maximum CCs of the WY with the SMTT do not appear over the area from 100°E to 130°E between 35°N and 50°N, which differs clearly from that shown in Fig. 1b. Because the WY index well reflects large-scale vertical shear over the South Asian monsoon area, the sea-land thermal contrast over the South Asian monsoon area is more directly tied with changes in zonal wind circulation. Consequently, the Indian southwest monsoon is closely

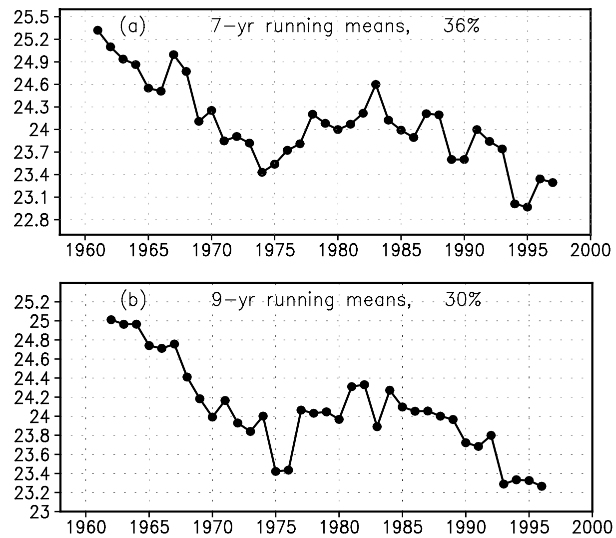

Fig. 3. (a) 7-yr and (b) 9-yr running means of the WY index. The percentage shown on the upper right corner in each figure stands for the explained variance. (Units: m s^{-1}).

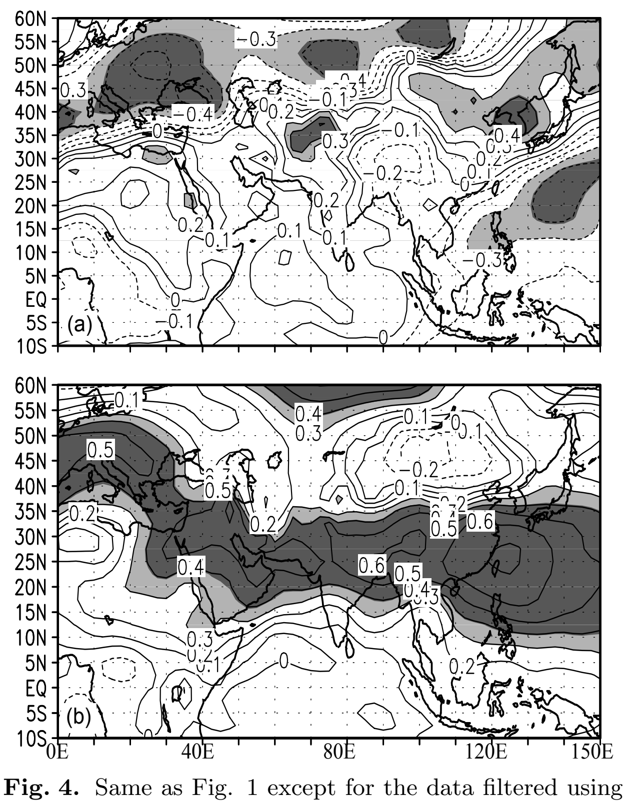

Fig. 4. Same as Fig. 1 except for the data filtered using a band-pass filter.

associated with the thermal contrast. In order to further describe possible connections of the SMTT with zonal wind circulation over the South Asian area, we chose regionally averaged zonal wind at 850 hPa to represent variations of the Indian summer monsoon intensity (Fig. 5a) (hereafter ZW index). The reason for this, on the one hand, is because 850-hPa wind variations reflect variations of the corresponding convective heating better than the upper-level circulation or vertical shear (Wang et al., 2001). On the other hand, the more important reason is that regionally averaged zonal wind in the shaded area at 850 hPa depicts very well trends of the Indian summer monsoon circulation and their connections with the TTV over East Asia (see text below). Moreover, tropospheric temperature is more strongly associated with the broad-scale monsoon circulation than the regional monsoon rainfall over the Indian subcontinent (Liu and Yanai, 2001).

Figure 5b shows correlation coefficients of the ZW index with the IMR and the WY indices exceeding the 0.01 significance levels. However, the value of the CC between the ZW index and the IMR is not as high as we expected. The main reason may be that the IMR is only part of the monsoon precipitation (Goswami et al., 1999). But the CC between the WY index and the IMR is 0.49 for 41 samples (1958–1998), which obviously differs from the previous studies due to different samples (Webster and Yang, 1992; Goswami et al., 1999). Although the CC is 0.49, the relationship

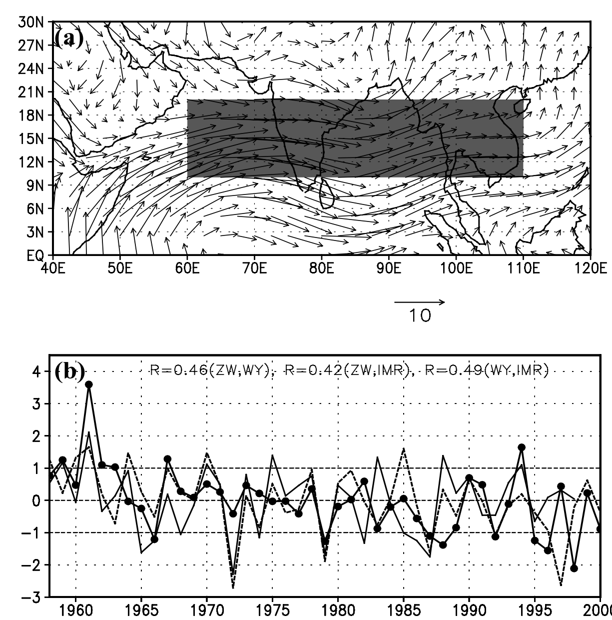

Fig. 5. (a) Summer (June–September) 850-hPa wind field averaged for 1958–2000. Units: m s^{-1}. The grid values of zonal winds for the shaded region (10°–20°N, 60°–110°E) are averaged to define the intensity index of the Indian summer monsoon circulation. (b) Interannual variations of the normalized IMR (Indian Monsoon Rainfall) (thin solid), WY (Webster and Yang) (dashed) and ZW (Zonal Wind) indices (thick solid). R is correlation coefficient.

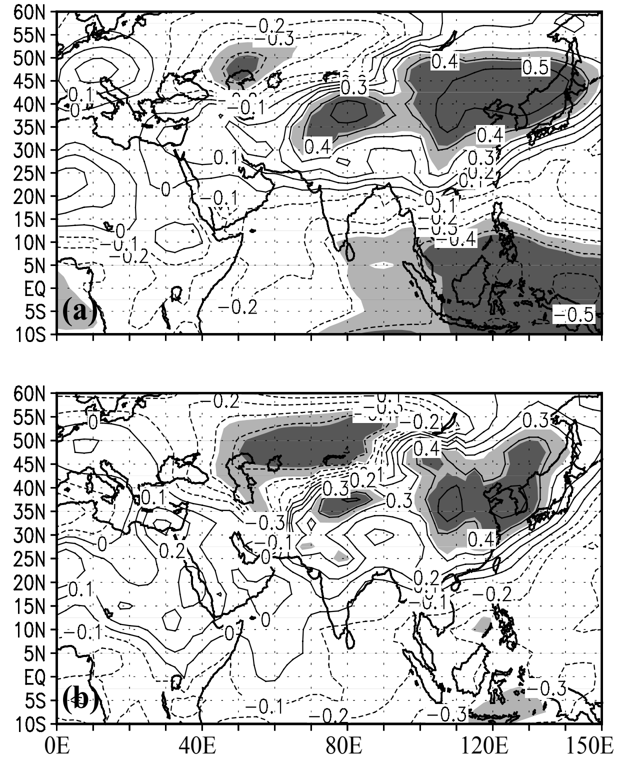

Fig. 6. Spatial distributions of CCs of the tropospheric mean temperature averaged from 200 hPa to 850 hPa with (a) the ZW index on interannual timescales, (b) the ZW index on interdecadal timescales. Interval is 0.1. The light and heavy shaded areas denote CCs above the 0.05 and 0.01 significance levels, respectively.

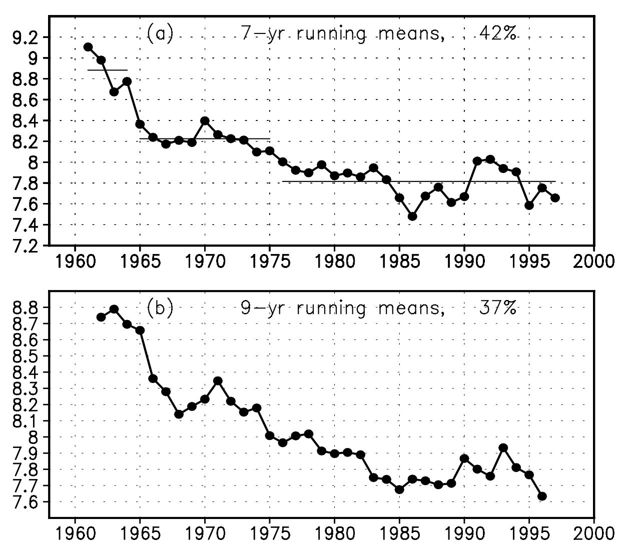

Fig. 7. Same as Fig. 3 except for the ZW index.

between them is not close, particular after 1980 (Fig. 5b). Ailikun and Yasunari (2001) also suggested that the WY index is more closely related with convective activity over the western Pacific, and not closely related with that over the Indian monsoon region. This is reasonable because Webster and Yang's original intention was to determine a measure of the variability of the broad-scale monsoon circulation for seeking a relationship with remote aspects of the general circulation. Figure 5b clearly displays a decreasing trend in the ZW time series.

The TTV over the east of 70°E, particularly over East Asia and the tropical area (east of 70°E and south of 10°N), shows high correlations with the ZW index on interannual timescales (Fig. 6a). On interdecadal timescales, the distribution of CCs (Fig. 6b) exhibits similar features to that shown in Fig. 6a over East Asia. This means that the intensity of the Indian summer monsoon circulation is closely related to the TTV over East Asia on both interannual and interdecadal timescales. Figure 7 shows the interdecadal trend of the Indian summer monsoon circulation in terms of 7-yr and 9-yr running means. Obviously, there is a decaying trend in the Indian summer monsoon circulation intensity after the mid-1960s. For the 7-yr running means of the ZW index, two regime shifts occurred in circa 1965 and 1976, respectively, which is very consistent with changes in the TTV over East Asia shown in Fig. 2. For the 9-yr running means, the turning points of the regime shifts are circa 1966 and 1975, respectively; for the 11-yr running means, they are circa 1967 and 1976 (figures not shown), respectively. A little difference in the turning points is reasonable due to the difference in the running means. Compared to the WY index, the ZW index better describes the downwards trends on interdecadal timescales, and its variation shows a more close association with the TTV over East Asia. This is also the major reason to choose regionally averaged zonal wind at 850 hPa as a measurement of the Indian summer circulation intensity.

In addition, since 1965 summer rainfall derived from 28 stations in North China was characterized by a decreasing trend (Fig. 8a; Figure 8c indicates locations of 28 stations), which is very consistent with previous studies (Huang et al., 1999; etc.). A possible reason for this may be the weakening of the thermal depression arising from the SMTT's decrease in East Asia, which suppresses convective activities and leads to a decease in rainfall. Furthermore, the 7-yr running mean of the IMR was below normal in most summers during the period of 1963–1989 (Fig. 8b). Since 1990, the IMR returned to normal state. From Fig. 8b, it is clear that the regime shifts in the rainfall time series occurred in the summer of 1963, which is consistent with the earlier study by Kripalani and Kulkarni (2001). The dis-

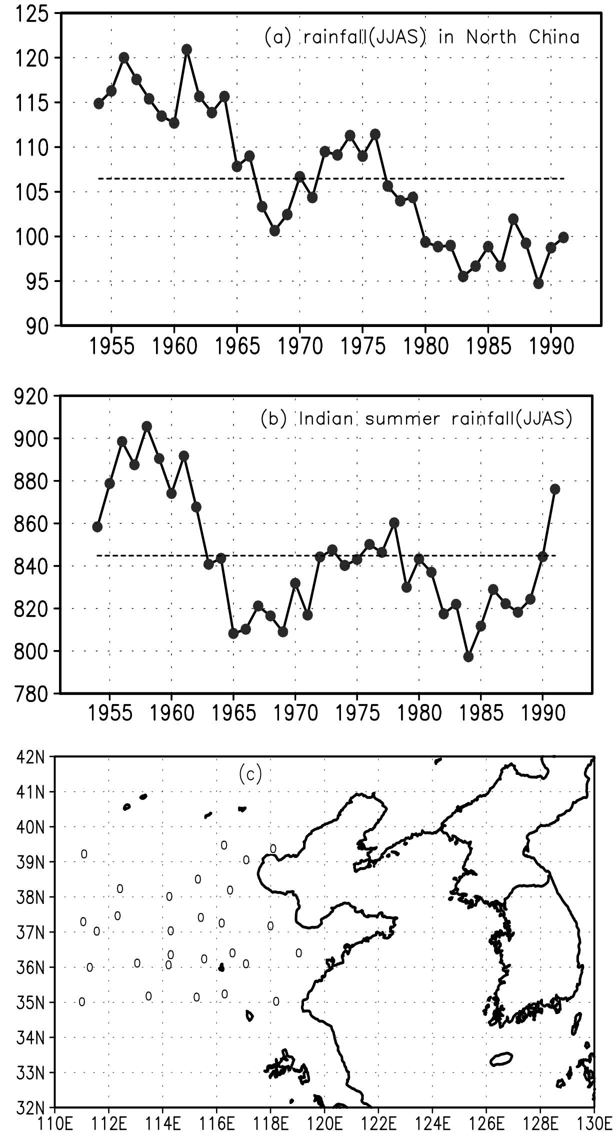

Fig. 8. The 7-yr running means of (a) summer rainfall of 28 stations in North China and (b) the IMR, Units: mm; (c) locations of 28 stations in North China.

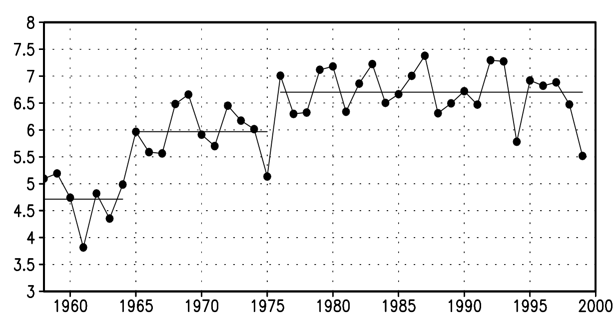

Fig. 9. Differences of the regionally-averaged tropospheric mean temperature (the tropical western Pacific and the maritime continent (10°S–10°N, 100°–150°E) minus East Asia (35°–50°N, 100°–130°E), Units: °C.

crepancy between Fig. 7 and Fig. 8b on major turning points is apparent. The major reason for this might be that the IMR is only a part of the summer rainfall in the South Asian Monsoon region. On the other hand, it is impossible to represent summer rainfall in the whole monsoon region in terms of the monsoon circulation intensity. Even if investigators utilize the same IMR data, there are some differences between their conclusions on turning points of the IMR due to their different methods (Parthasarathy et al., 1990; Kripalani and Kulkarni, 2001). The evidence demonstrates that the abrupt variation of the summer SLP pattern (EOF1) appeared in circa 1965, whereas the jump of the 500-hPa height field occurred in circa 1962 (Yan et al., 1991). Furthermore, Schaefer (2001) revealed that a high frequency of dry years can be observed during 1899 and 1920 and after 1965, based on all-Indian annual rainfall series (1871–1999) (see his Fig. 2). Therefore, major turning points that occurred in the 1960s exhibit some differences with different parameters. Consequently, one of the possible reasons for the weakening of the Indian summer monsoon circulation may be attributed to keeping negative mean tropospheric temperature anomalies over East Asia, which modifies the tropospheric thermal contrast over the continent and the ocean. Kripalani et al. (1997) and Kripalani and Kulkarni (1999) argued that the epochal IMR variability is more associated with events in the Northern Hemisphere mid-latitudes than over the tropical oceanic regions.

We chose the regionally averaged SMTT differences of the tropical region (10°S–10°N, 100°–150°E) minus East Asia (35°–50°N, 100°–130°E) to represent the tropospheric thermal contrast over the continent and the ocean, as shown in Fig. 9. Temperature differences are positive, reflecting that the SMTT is higher over the tropical region than East Asia. Therefore, the role of the thermal contrast over the tropical region and East Asia is to weaken the Indian summer monsoon circulation rather than to increase it. Obviously, the regime shifts that occur in the time series of temperature differences coincide well with those shown in Fig. 7.

Figure 10 shows the spatial distribution of the SMTT anomalies. During the period 1958–1964, the Asian continent and part of the northwestern Pacific was the area of greatest warming in the Northern Hemisphere with the largest positive anomaly exceeding 1.8°C over the area 40°–50°N and 90°–110°E (Fig. 10a), whereas, the SMTT over the south of 20°N and east of 60°E was nearly normal. Thus, such distribution of the SMTT anomalies reduced the land-sea thermal contrast (Fig. 9), corresponding to a strong

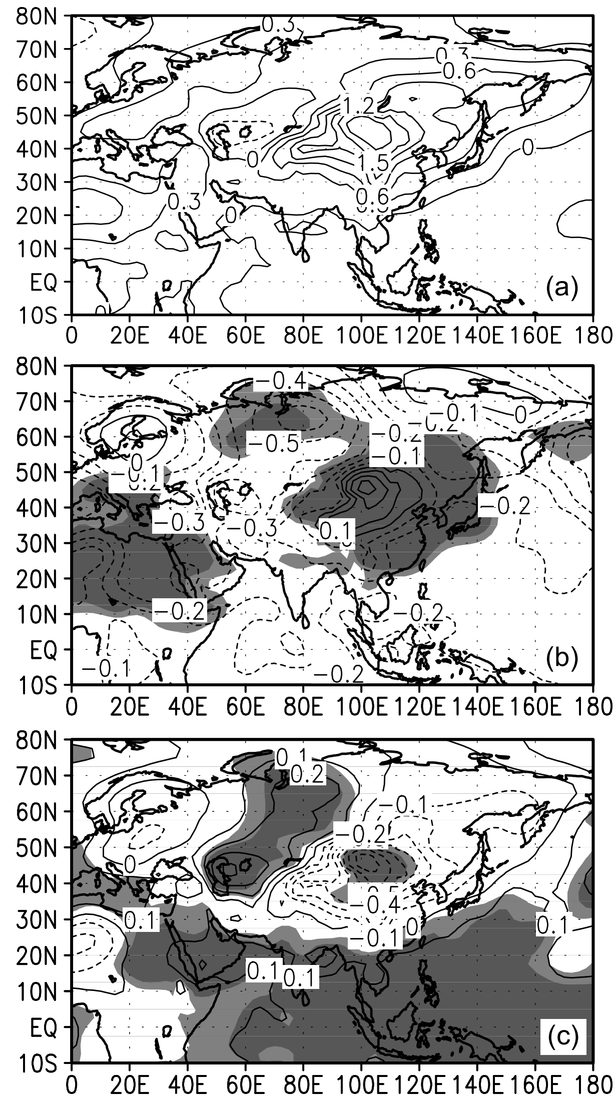

Fig. 10. Composites of the tropospheric mean temperature anomalies for the period (a) 1958–1964, (b) 1965–1975 and (c) 1976–1999. The light and heavy shaded areas represent differences (b) 1965–1975 minus 1958–1964 and (c) 1976–1999 minus 1965–1975 above the 0.05 and 0.01 significance levels, respectively. Intervals: 0.3°C in (a), 0.1°C in (b) and (c).

epoch of the Indian summer monsoon (Fig. 7). In the summers of 1965–1975, compared with the preceding period, the eastern Asian continent SMTT dropped obviously with a magnitude exceeding 1.5°C, while the decrease in temperature was less than 0.3°C in the south of 20°N. As a result, the SMTT anomalies enhanced the land-sea thermal contrast (Fig. 9), which coincides with the first weakening of the Indian summer monsoon (Fig. 7). We also notice that the SMTT differences (1965–1975 minus 1958–1964) exceeding the 0.01 significance level mainly include the central and eastern Asian continent north of 20°N, East Asia, northern Africa, and southern Europe. However, no significant changes occur over the Indian Ocean and the northwestern Pacific. Consequently, the major reason for the first weakening of the Indian summer monsoon might be attributed to the significant changes in the SMTT over the East Asian and African monsoon regions. After 1976, the SMTT further dropped over the central and eastern Asian continent north of 30°N, compared with Fig. 10b, and the magnitude of the temperature decrease was over 1°C. Figure 10c obviously differs from Fig. 10b, viz. the significant warming appears over the tropical area south of 30°N. Therefore, the significant tropospheric warming over the tropical area might be associated with the second weakening of the Indian summer monsoon.

What mechanisms are responsible for the weakening in the Indian summer monsoon circulation after circa the mid-1960s? The preceding section shows that corresponding to the two weakening processes in the Indian summer monsoon circulation, the tropospheric temperature contrast exhibits significant differences over East Asia, Africa and the tropical area. The previous studies have already verified that the East Asian summer monsoon and the Indian summer monsoon are relatively independent of each other. Consequently, the tropospheric temperature variation over East Asia may not be influenced by the Indian summer monsoon. Consequently, the role of the tropospheric thermal-contrast between East Asia and the tropical area is to weaken westerlies over the area from the Indo-China Peninsula to the South China Sea (Fig. 9), which is responsible for the weakening of the Indian summer monsoon (Figs. 7 and 9).

4. Further evidences

In the previous sections, on the basis of the analysis of the reanalysis dataset, we revealed the weakening of the Indian summer monsoon circulation and its connections with tropospheric temperature variations in recent decades. In this section, we use station observations and those derived from station observations in the world to further demonstrate the existence of the regime shifts that occurred in circa the mid-1960s and the late 1970s. In East Asia, Beijing (39.48°N, 116.28°E) is a good meteorological station due to its longer observation records than others in the vicinity of Beijing. Evolutions of summer (June–September) SLP at Beijing clearly show interdecadal timescale variations superimposed on a linear trend (Fig. 11a). During the periods of 1951–1964 and 1981–1996, lower than normal summer SLP was evident, while during

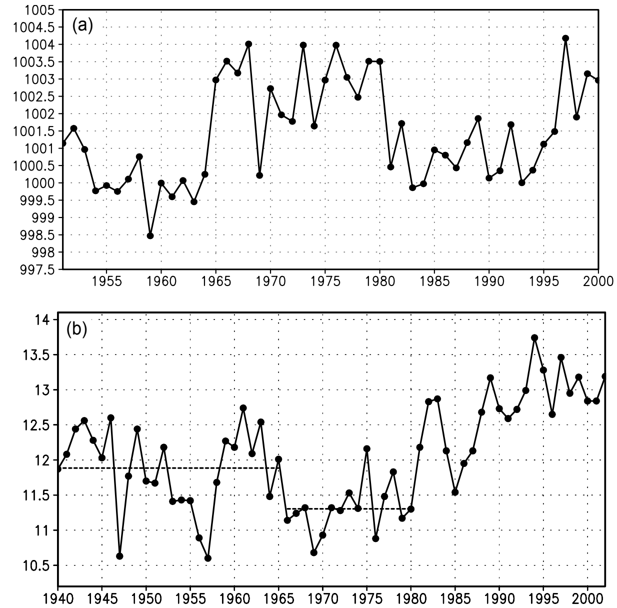

Fig. 11. Interannual variations of (a) summer SLP (hPa) and (b) annual mean surface air temperature (°C) at Beijing (39.48°N, 116.28°E). The dashed line denotes the epochal mean

the summers of 1965–1980, summer SLP obviously increased. The jumps in SLP mainly occurred in 1964–1965 and 1980–1981, respectively. Compared with Fig. 2, during the period of 1958–1964, the SMTT over East Asia was warmer than the long-term climatic average, and corresponded with a strong thermal depression (Fig. 11a). During 1965–1980, the weakened thermal depression, which may be partly attributed to the SMTT's decrease in East Asia, suppressed convective activities that led to a decrease in summer rainfall (Fig. 8a). The surface air temperature at Beijing also experienced apparent epoch variations, i.e. before 1965 and after 1981 surface air temperature was warmer than that in the time between them (Fig. 11b). Consequently, Fig. 11 provides further evidences about the existence of the regime shift in circa the mid-1960s. Meanwhile, the station observations also verify the quality of the reanalysis data. Obviously, the regime shift in the mid-1960s was apparent in East Asia and the Northern Hemisphere, while that in the late 1970s was related with the global warming.

5. Conclusions

Based on the NCEP/NCAR reanalysis data, Indian summer rainfall and stations observations, this paper investigated the phenomenon and the cause of the weakening of the Indian summer monsoon in recent decades. This paper focused on the possible connections between the weakening of the Indian summer monsoon and the tropospheric mean temperature variations over East Asia and the tropical area from the Indian Ocean to the western Pacific. The conclusions can be drawn as follows:

(1) The Indian summer monsoon circulation has experienced two weakening processes during recent decades. The first occurred in circa the mid-1960s; and the second appeared in the late 1970s. The first weakening of the Indian summer monsoon circulation coincides very well with climate variations that occurred in East Asia, particularly in the tropospheric mean temperature.

(2) The role of the thermal contrast in the tropospheric mean temperature between East Asia and the tropical area from the eastern Indian Ocean to the tropical western Pacific is to weaken the Indian summer monsoon circulation.

(3) The cause of the first weakening of the Indian summer monsoon circulation, which occurred in circa the mid-1960s, may be attributed to significant tropospheric temperature decreases in East Asia and the African monsoon region. The second weakening may be attributed to significant tropospheric warming over the tropical area from the Indian Ocean to the western Pacific.

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